

A Variscan slow-spreading ridge (MOR-LHOT) in Limousin (French Massif Central): magmatic evolution and tectonic setting inferred from mineral chemistry

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ABSTRACT

The Limousin ophiolite (French Massif Central) occurs as elongate bodies forming a (nearly) continuous suture zone between two major lithotectonic units of the French Variscan belt. The mantle section of the ophiolite is made of diopside-bearing harzburgite, harzburgite and dunitite characteristic of a lherzolite-harzburgite ophiolite type (LHOT). The plutonic section is essentially composed of troctolites, wehrlites and gabbros locally intruded by ilmenite-rich mafic dykes. All the rocks were strongly affected by an ocean-floor hydrothermal metamorphism. The composition and evolution of primary magmatic phases (olivine, clinopyroxene, plagioclase and spinel) throughout the lowermost magmatic sequence correspond to those described in oceanic cumulates (ODP data). The Limousin ophiolite is thus of MOR type instead of SSZ type. The whole lithological section, the mineral chemistry, the extensive hydrothermal oceanic alteration and the relatively thin crustal section are typical of a slow-spreading ridge ocean (i.e. Mid-Atlantic ridge). Comparison of the Limousin ophiolite with other ophiolites from European Variscides suggests that the oceanic domain was actively spreading during the Late Palaeozoic and extended from the Armorican massif to the Polish Sudetes.

KEYWORDS: LHOT, MOR, slow-spreading ridge, Variscan, Limousin, France.

Introduction

OPHIOLITES are important geological markers for reconstructing the geodynamic evolution of orogenic belts. They correspond either to an episode of ocean spreading above a subduction zone (supra subduction zone ophiolites: SSZ) or to ocean spreading at a mid-ocean ridge not related to any subduction zone (mid-ocean ridge ophiolites: MOR). The differences between MOR and SSZ ophiolites were reviewed by Pearce (2003). They are summarized below.

Plagioclase is more abundant in ultramafic cumulates of MOR ophiolites (Church and Riccio, 1977; Parlak *et al.*, 2002) while amphibole

is common in SSZ ophiolites (Beard, 1986). The ferromagnesian phases (olivine, clinopyroxene) are more Mg-rich and plagioclase is usually more calcic in SSZ ophiolites (Hébert *et al.*, 1989; Parlak *et al.*, 2002). The SSZ ophiolites are globally enriched in LILE while MOR ophiolites are enriched in HFSE (Miyashiro, 1975; Pearce, 2003).

The use of whole-rock geochemical data to distinguish between a SSZ or MOR affinity of the cumulate sequence of the Limousin ophiolite would not be determinant because: (1) ocean-floor hydrothermal metamorphism has probably changed the primary bulk-composition; (2) the whole-rock composition of cumulates is influenced by fractional crystallization processes. Moreover, in the absence of an extrusive sequence, it is not possible to use classical

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discrimination diagrams for basalts (Pearce, 2003).

The Limousin ophiolite, as it was defined by Dubuisson *et al.* (1989), is made up of ultramafic and basic rocks in association and is located at the contact between two major lithotectonic units of the French Massif Central. In the 1980s, these rocks were the subject of strong debate between proponents of magmatic intrusions (review in Egal *et al.*, 1985) until Santallier (1995) proposed the serpentinized peridotites as slices of mantle rocks, and of a dislocated ophiolite (review by Dubuisson *et al.*, 1989). The latter have definitely listed the co-genetic characters of the mantle and magmatic rocks and interpret the whole bodies as relics of a fossil oceanic lithosphere. The main arguments were: the existence of a depleted mantle series (basal lherzolites, harzburgites and dunites); the presence of podiform chromite deposits; the association of mantle rocks passing to basic magmatic rocks through feldspar wehrlites; the MORB-type characters of the *REE* patterns in gabbros. The main metamorphic event affecting these basic rocks is an ocean-floor metamorphism (Berger *et al.*, 2005). This result has strengthened the interpretation of the whole series as an ophiolite.

Here we discuss the mineral chemistry in the lower crustal section of the Limousin ophiolite. We will first discuss the tectonic setting of this ophiolite and the geodynamic implications of a SSZ or MOR affinity.

Geological setting

The Limousin area belongs to the western part of the French Massif Central and is part of the European Variscan Orogenic belt (Fig. 1). The ophiolites mark a suture zone between two major units (Dubuisson *et al.*, 1988): the upper allochthon consisting of metagreywackes and containing numerous lenses of basic, eclogite-derived rocks; and the intermediate allochthon consisting of leucocratic gneisses with Ordovician protoliths (Lafon, 1986). Two major oceanic domains have been recognized in the Variscan in Western Europe: the Rheic Ocean, best represented by the Cap Lizard Ophiolite, and the Massif Central-Galicia Ocean mostly represented by numerous eclogites lenses in the upper allochthon (Matte, 2001; Pin and Paquette, 2002). The Limousin ophiolite probably belongs to the latter southern domain but its age and its extension remain unclear. For Matte (2001) and Pin and Paquette

(2002), the ocean basins opened sometime between the Ordovician to lowermost Carboniferous (490–360 Ma), while for Ledru *et al.* (1989) the oceanic domains closed at ~400 Ma. Destruction of oceanic plates by subduction was active in the lower Devonian and Early Carboniferous (see discussion) and collision probably began at ~350 Ma (Pin and Paquette, 2001).

The ophiolite bodies are elongate massifs forming a nearly continuous 25 km long and 0.2–1 km wide band of mafic-ultramafic rocks dismembered by late-orogenic strike-slip faults (Fig. 1B).

The lithology of the various bodies is variable; some massifs are composed of harzburgite-derived serpentinites only (Lonzac, Queue d'âne), whereas others present an association of such serpentinites together with wehrlites, troctolites and gabbros (La Plagne, La Flotte), the former often not present (La Porcherie). We have concentrated our field work on these three most complete massifs because they present more abundant relics of magmatic phases. The ideal synthetic reconstructed sequence comprises basal sheared mantle harzburgite, granular clinopyroxene-free mantle harzburgite, mantle dunite with localized channelled chromite deposits, feldspar-rich wehrlites, troctolites and gabbros (Fig. 1C). Whenever associated in the field, these lithologies always show a polarity consistent with this ideal sequence, and all lithologies have been affected by ocean-floor hydrothermal metamorphism (Berger *et al.*, 2005).

Petrographic description

Harzburgites are highly serpentinized and chloritized rocks. Textures vary from highly deformed (in mantle conditions) mylonites at the floor of the sequence (Dubuisson *et al.*, 1989) to granoblastic harzburgites. In the mylonite facies (lower harzburgites), clinopyroxene modal proportions are very small but can reach 5% in some samples. In contrast, the granoblastic harzburgites (upper harzburgites) have virtually no relics of the original paragenesis, which is consistent with the worldwide observation that this granoblastic shallower and initially colder facies is usually much more serpentinized. The latter harzburgites are also locally cut across by small gabbroic intrusions or dykes.

Dunites are serpentinites with scarce relics of olivine and spinel. Pods of altered chromite (Cr-

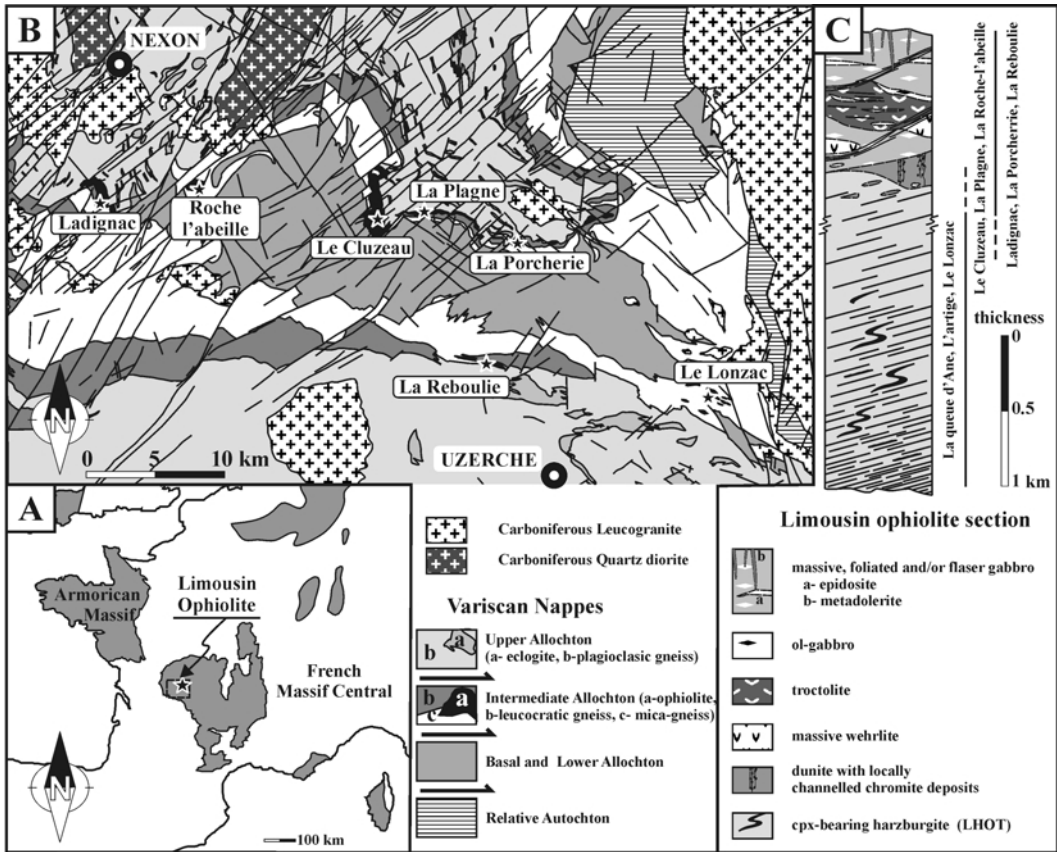


FIG. 1. Geological setting of the Limousin ophiolite. (A) The studied area in the Variscan French Massif Central. (B) Schematic geological map of the studied area in Limousin. (C) Reconstructed Limousin ophiolite section modified after Dubuisson *et al.* (1989).

magnetite) are present within these dunites, but are no longer of any economic value.

Wehrlites consist essentially of olivine and clinopyroxene with minor plagioclase and Cr-bearing spinel. Hydrothermally-altered wehrlites are made of serpentine and/or amphibole (replacing olivine) and chlorite (replacing clinopyroxene).

Troctolites are serpentinized olivine- and plagioclase-bearing rocks with minor clinopyroxene and orthopyroxene and Cr-bearing spinel. The modal proportions of plagioclase (5–80%) and olivine (90–20%) are highly variable, even in a given sample. The troctolites can thus be interlayered with wehrlites. Hydrothermal alteration has partly transformed olivine into serpentine or pargasite and plagioclase into a mixture prehnite+chlorite.

Layered gabbros are extensively amphibolitized. Relics of clinopyroxene (only observed in the lowermost crustal section) are rare while plagioclase remains relatively fresh. A few samples of olivine-gabbro have been collected. They contain up to 10% of olivine. Modal proportions are also variable (plagioclase: 30–90%; amphibolitized clinopyroxene: 60–5%). We have also observed minor proportions of orthopyroxene, aluminous spinel, ilmenite, Ti-pargasite and apatite. Some fine-grained ilmenite-rich amphibolites have been sampled within the gabbroic sequence; they could represent dykes of basaltic composition.

Hydrothermal ocean-floor alteration has transformed the gabbros into amphibolites (plagioclase + amphibole + titanite) with significant amounts of prehnite, chlorite, zeolites, epidotes and Cu-Fe-

Ni-Zn sulphides. Some true epidiosites have also been found (clinozoisite + diopside + prehnite + actinote). The gabbros are frequently cut across by veins of prehnite, amphibole, chlorite, grossular, hydrogrossular and serpentine.

The gabbros are generally undeformed to slightly deformed. In this case, rare relics of a cumulate texture (euhedral laths of plagioclase with interstitial amphibole replacing clinopyroxene) are still seen. Some gabbros have been transformed into gneiss or mylonites, probably by shearing in oceanic conditions (Berger *et al.*, 2005).

Mineral chemistry

Relict magmatic minerals have been analysed by electron microprobe at the CAMST (University of Louvain-La-Neuve) using a Cameca SX 50 probe. The operating conditions involved a current beam of 20 nA, an accelerating voltage of 15 kV and a counting time of 10–20 s per element. The analyses of silicate minerals in mantle dunites and harzburgites have been compiled from the work by Dubuisson (1988).

Olivine

The composition of olivine varies as a function of lithology. The Fo content is close to 91 in the dunites and in the range 92–88 in the harzburgites. In the wehrlites, it is slightly higher but overlapping (Fo_{87–83}) that for troctolites (Fo_{85–80}). One troctolite has an anomalously high Fo content (89) in the range of that of harzburgites. Olivine from the olivine gabbros has the lowest Fo content (Fo_{72–67}).

Pyroxenes

The composition of relict diopside also varies with the host lithology (Fig. 2); it is Mg-rich in the mantle section (Mg#: 98–93) whereas it has lower Mg# values in the wehrlites (93–90), troctolites (92–88), ol-gabbros and gabbros (90–79).

Minor element composition of clinopyroxenes (Fig. 3) from the mantle section varies from 5.5 to 7.5 wt.% of Al₂O₃ and from 0.3 to 0.9 wt.% of Cr₂O₃. There is a general decrease in Al₂O₃ content with decreasing Mg# of the magmatic clinopyroxenes: from 4.8–3.5 wt.% of Al₂O₃ in the troctolite and wehrlites to 4.4–1.8 wt.% of Al₂O₃ in the gabbros. The same trends are

observed with Cr₂O₃: 0.9–0.3 wt.% in the wehrlites; 0.8–0.5 wt.% in the troctolites and 0.6–0.1 wt.% in the gabbros. The range of composition of the Limousin clinopyroxenes is quite similar to those sampled by drill cores in ODP legs 153 (Mid-Atlantic ridge; Cannat *et al.*, 1997) and 176 (Southwest Indian ridge; Niu *et al.*, 2002) and to those of oceanic cumulates compiled by Hébert *et al.* (1989) and Elthon *et al.* (1992).

Magmatic enstatite has only been observed in one plagioclase-rich troctolite (Mg# = 85) and in one olivine-gabbro (Mg# = 76).

Plagioclase

Magmatic plagioclase is relatively well preserved in all lithological types. The plagioclase from wehrlite is relatively Na-rich (An_{62–64}) when compared to the plagioclase composition in troctolites (An_{75–69}). The An content of plagioclase varies from An₆₈ to An₆₀ in olivine-gabbros and from An₇₆ to An₄₈ in olivine-free gabbro (Fig. 4). These data are comparable to those observed in oceanic samples of ODP leg 176 (Niu *et al.*, 2002).

Spinel

Spinel is a common accessory phase of wehrlites and troctolites but it is absent in gabbros (Fig. 5). It generally shows coronas or fractures filled with nearly pure magnetite, which is a common feature of altered spinels. The composition of spinels in the mantle section has been described by Dubuisson (1988), with Mg# values varying from 58 to 78 and Cr# values between 20 and 31. Partitioning of Mg vs. Fe between olivine and spinel obeys the same law as for major ophiolites

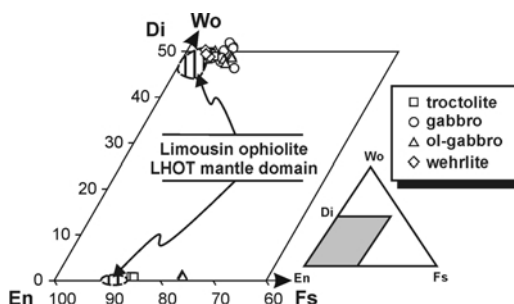


FIG. 2. Composition of pyroxenes in the quadrilateral diagram. Mantle clinopyroxene data from Dubuisson (1988).

(e.g. Newfoundland) and simply describes a blocking temperature for the olivine-spinel exchange reaction, in agreement with the experimental evidence of fast re-equilibration under mantle conditions.

In the crustal section, the Mg# varies from 68 to 18 in the wehrlites and from 69 to 48 in the troctolites. As for Cr#, it is positively correlated with Mg# and varies from 68 to 15 in the wehrlites and from 48 to 12 in the troctolites. These values fall outside the spinel field for Oman and oceanic cumulates, but they are nearly the same as for altered spinels from serpentinites analysed by Burkhard (1993). In gabbros, the oxide is a Ti-phase: ilmenite or rutile when the gabbro is relatively fresh, and titanite when it is amphibolitized.

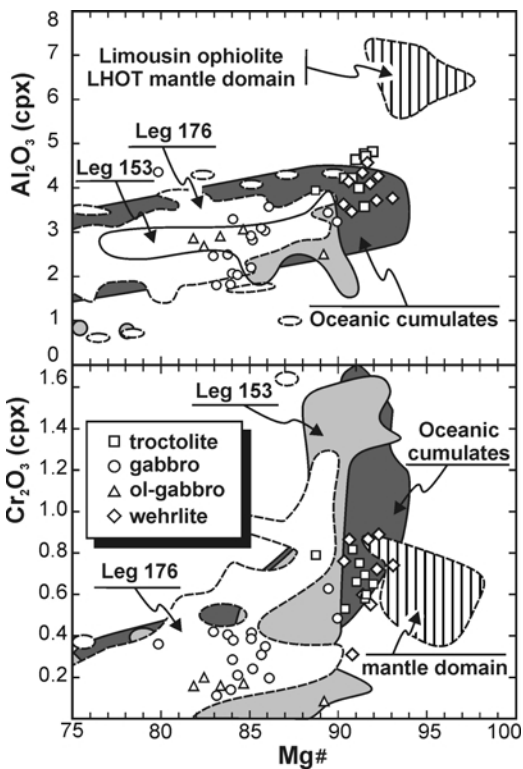


FIG. 3. Minor elements vs. Mg# for the Limousin clinopyroxenes compared to data from oceanic cumulates (Hébert *et al.*, 1989), Leg 153 cumulates (Cannat *et al.*, 1997) and Leg 176 cumulates (Niu *et al.*, 2002). Data for the Limousin mantle domain from Dubuisson (1988).

Covariation diagrams (Fig. 6)

The Mg# of clinopyroxene and the Fo content of olivine are positively correlated but there is a compositional gap between mafic and ultramafic rocks. Broadly speaking, the Limousin ophiolite is comparable with the plutonic suite of Leg 176 (Niu *et al.*, 2002) and to oceanic cumulates.

The Mg# of clinopyroxene and the An content of plagioclase are not correlated. This may be related to the wide range of plagioclase composition for restricted Mg# variations of clinopyroxenes in ultramafic cumulates. Nevertheless, the rather small An content in plagioclase is similar to those for oceanic cumulates (Hébert *et al.*, 1989) and Leg 176 cumulates (Niu *et al.*, 2002) and is distinct from the composition domain of SSZ ophiolites as illustrated by Troodos cumulates (Hébert and Laurent, 1990).

The extended range of An content for plagioclase of ultramafic cumulates and the Fe and Na enrichment observed in olivine and plagioclase, respectively, of olivine-gabbros is shown on the An(pl) vs. Fo(ol) diagram (Fig. 6). Once more, the composition of these phases is more comparable to those analysed in oceanic cumulates (Hébert *et al.*, 1989; Niu *et al.*, 2002) than to SSZ-derived ophiolites (Troodos; Hébert and Laurent, 1990).

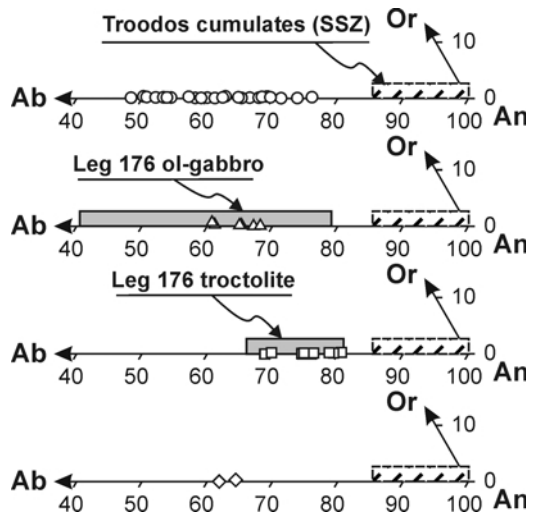


FIG. 4. Composition of plagioclase as a function of the lithological type. Data for Leg 176 from Niu *et al.* (2002) and data for Troodos from Hébert and Laurent (1990). Same symbols as in Fig. 2.

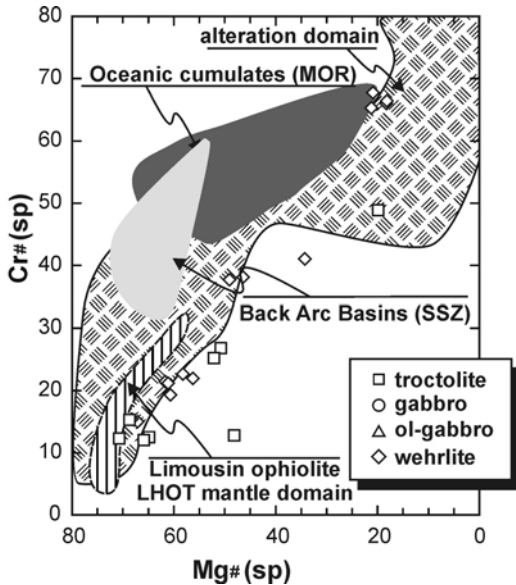


FIG. 5. Spinel composition in the Cr# vs. Mg# diagram. Altered-spinel field from Burkhard (1993); back-arc basin spinels from Dick and Bullen (1984); oceanic-cumulate field compiled from Elthon *et al.* (1992) and Niu *et al.* (2002).

Discussion

Magmatic evolution in the cumulates of the Limousin ophiolite

Classical trends of differentiation have been presented in the previous section. The Mg# of ultramafic cumulates is higher than in the gabbros; it represents a continuous decrease in the Mg# of the crystallizing melt. The covariation diagrams show that the decrease in Mg# is accompanied by a decrease in An content of plagioclase due to the relative decrease in Ca content of the magma when compared to Na in the magmatic liquid.

Minor elements in clinopyroxenes are also useful to infer processes of differentiation. The decrease in Cr is proof of the early precipitation of Cr-spinel, as was observed in the wehrlites and the troctolites. Decrease in Al with decreasing Mg# (and associated Si increase) may represent early crystallization of plagioclase, which is confirmed by its abundance in troctolites and wehrlites.

Dubuisson *et al.* (1989) proposed that the wehrlites are the result of impregnation of mantle dunite by a basaltic melt. We do not agree with this interpretation because: (1) wehrlites are sometimes interlayered with troctolites;

(2) all the silicate and oxide phases have compositions closer to those for troctolites than to those for mantle harzburgites and dunites.

Therefore, the basaltic liquids first crystallized olivine and spinel, but it is difficult to know if the next crystallizing phase was plagioclase or pyroxene. Plagioclase became the main magmatic phase in gabbros along with clinopyroxene and ilmenite. More differentiated rocks such as Fe-rich gabbros, dolerites or plagiogranites have not been found. Nevertheless, some amphibolites are characterized by a small Mg# for amphibole (down to 60) and by a small An content for relict magmatic plagioclase (down to 50), and they may represent more differentiated amphibolitized gabbros. Some ilmenite-rich fine-grained amphibolite has also been found as dykes in gabbros; they could also represent amphibolitized dolerites.

The Limousin ophiolite: a fossil slow-spreading ocean

The Limousin ophiolite has many characteristics in common with MOR-derived ophiolites: (1) the abundance of plagioclase in ultramafic cumulates and its relatively small An content (Elthon *et al.*, 1992; Parlak *et al.*, 2002; Pearce, 2003); (2) the absence of websterites (or pyroxenites) whereas they are generally present in SSZ ophiolite such as the Troodos ophiolite (Malpas, 1990; Parlak *et al.*, 2002); (3) the presence of ilmenite-rich amphibolites (presumably derived from micro-gabbros) that probably have a high whole-rock Ti content like MORBs (Serri, 1981; Pearce, 2003); (4) the scarcity of hydrous magmatic phases. The absence of highly calcic plagioclase together with the absence of a magmatic hydrous phase argue that the parental oceanic magma was anhydrous (Sisson and Grove, 1993).

The Limousin ophiolite has also a lot of features in common with the Iherzolite-harzburgite ophiolite type (LHOT, corresponding to present slow-spreading ridges) as defined by Nicolas and Boudier (2003): (1) a mantle section made of diopside-bearing and diopside-free harzburgites and dunites; (2) the abundance of wehrlites in the lowermost oceanic crust; (3) the high temperature of deformation for the rocks of the mantle section (Dubuisson, 1988); (4) the extensive ocean-floor hydrothermal alteration (10–100% of alteration; Berger *et al.*, 2005); (5) the apparently heterogeneous and thin crust, which may explain in part why it is locally absent in massifs of specific geographic distribution (Lonzac, Queue d'Ane).

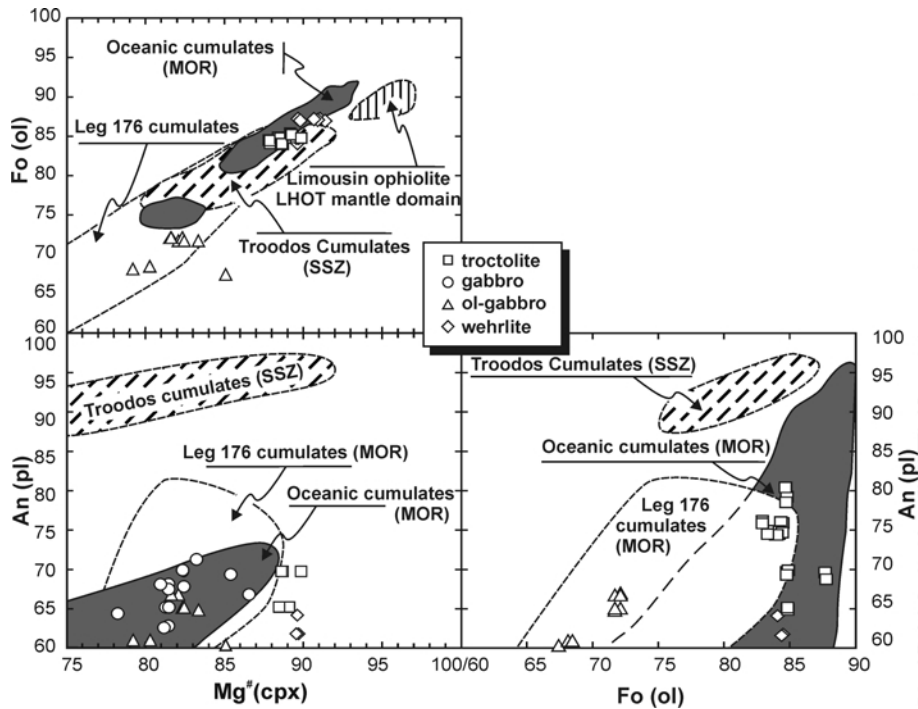


FIG. 6. Covariation diagrams involving clinopyroxene, olivine and plagioclase compared to phases in oceanic cumulates (Hébert *et al.*, 1989) and Leg 176 cumulates (Niu *et al.*, 2002). Data for the Limousin mantle domain from Dubuisson (1988). Troodos mineral compositions after Hébert and Laurent (1990).

Heterogeneous and thin oceanic crust comparable to the crustal section of the Limousin ophiolite is well known in present slow-spreading ridges (Cannat *et al.*, 1995). In this environment, the oceanic lithosphere is not homogeneous; it consists of a thin magmatic crust resting upon the uppermost mantle section and representing magmatic centres (high magmatic fluxes) alternating with areas where mantle-derived serpentinites crop out, the magmatic activity being restricted to small gabbroic intrusions and mafic dykes within the upper mantle. In such a thin crust, the ocean water can penetrate deeper than the petrologic Moho discontinuity, and the geophysical Moho is then outlined by the transition of serpentinized peridotite to unaltered mantle rocks. Such characteristics explain the high degrees of ocean-floor alteration in the Limousin ophiolite (Berger *et al.*, 2005).

Geodynamic implications

The Limousin ophiolite remnants characterize a slow-spreading ridge and constitute evidence for

the existence of a true oceanic domain not related to a subduction zone, in the central part of the French Massif Central during Variscan times. The age of the Limousin ophiolite remains unknown. Nevertheless, the geological setting of the ‘Limousin Ocean’ and its relationship to the other oceanic basins in the European Variscan belt could be used to constrain the age and origin of this ocean.

A Cambro-Ordovician oceanic domain in middle Europe has been proved by the presence of Siluro-Devonian eclogite occurrences with ocean-derived Ordovician protoliths and by Cambro-Ordovician SSZ ophiolites (Fig. 7; Pin, 1990).

However, there are two strong arguments for the existence of an oceanic domain during the late Devonian and/or the Early Carboniferous (Pin, 1990): (1) a Devono-carboniferous subduction marked by numerous eclogite occurrences all across Variscan Europe (Fig. 7); and (2) Devono-Carboniferous mafic-ultramafic associations with oceanic affinities (Fig. 7).

The Limousin, MOR-derived ophiolite was not generated in the same tectonic setting as the

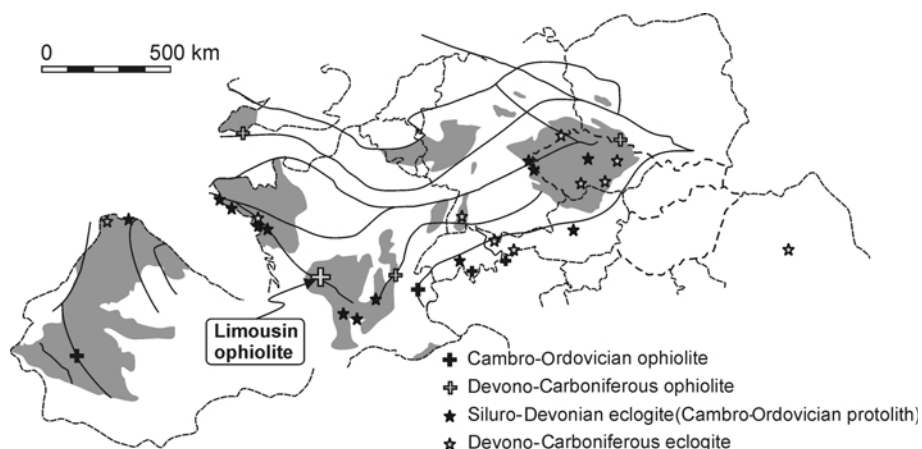


FIG. 7. Location of the Limousin ophiolite remnants and of the other Variscan ophiolites and HP markers (eclogite) in the West European Variscides (N. Spain and Cabo Ortegal – Ordóñez Casado *et al.*, 2001; Rodríguez *et al.*, 2003; S. Spain – Gómez-Pugnaire *et al.*, 2003; Groix, Vendée, Massif Central – Pin and Peucat, 1986 and references therein; Bosse *et al.*, 2000; Paquette *et al.*, 1995; Leloix *et al.*, 1999; Chamrousse – Ménot *et al.*, 1988; Schwarzwald – Kalt *et al.*, 1994; Polish Sudetes – Pin *et al.*, 1988; Brueckner *et al.*, 1991; Bohemian – Beard *et al.*, 1992; Schmädicke *et al.*, 1995; Svojtka *et al.*, 2002; von Quadt and Gebauer, 1993; Stosch and Langmuir, 1990; Alps – Miller and Thoni, 1995; Schaltegger *et al.*, 2002; von Raumer *et al.*, 2002; Faryad *et al.*, 2002; the Carpathians – Medaris *et al.*, 2003).

heterogeneous Chamrousse Ordovician SSZ ophiolite (Pin and Carne, 1987). Moreover, the Limousin ophiolite did not register a HP-metamorphism like the MORB-derived eclogites with Ordovician protoliths that are widespread in the French Massif Central. We propose that the Limousin ophiolite belongs to the Late-Devonian oceanic domain of the northern French Massif Central evidenced by Pin and Paquette (2001). Pin *et al.* (1988) suggested that ophiolite remnants with MORB characteristics and devoid of high-grade metamorphic recrystallization are probably relics of a Late Devonian/Early Carboniferous oceanic domain.

As shown in Fig. 7, the Late Devonian oceanic domain probably extended from Galicia to the Bohemian massif. This ocean basin was probably very wide but its slow-spreading ridge affinity tells us that it was probably not a large ocean; it was comparable to the Red Sea or to the Central Atlantic.

Conclusion

The lithological sequence of the Limousin ophiolite, the pervasive imprint of an ocean-floor hydrothermal alteration and the mineral chemistry of the magmatic minerals are similar to what is observed in the plutonic section of slow-

spreading ridge oceans (MOR type, e.g. Mid-Atlantic ridge). The Limousin ophiolite is also comparable to other late Palaeozoic ophiolite occurrences devoid of any extensive high-grade metamorphic recrystallization. The exact age and extension of this ocean remain largely unknown but, by comparison to other ophiolite occurrences in Central Europe, the Limousin ophiolite could represent a portion of a small Late Devonian/Early Carboniferous oceanic basin that extended from Galicia to the Eastern Bohemian massif. A geochronological study will better constrain its position and its influence on the major tectonomagmatic events of the Variscan orogen in Central Europe.

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